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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

ELSEVIER

# Short wavelength free electron lasers in 1994

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The following table lists the existing and proposed relativistic free electron lasers (FELs) in 1994. The top part of the table lists existing FELs. These are substantially complete experiments that may not be operating at the present time. The bottom part of the table lists proposed FELs. Each FEL, existing or proposed, is identified by a location, or institution, followed by the FEL's name in parentheses. There are 46 experiments listed from 7 countries representing all continents in the northern hemisphere and indicating the international character of this field.

The first column of the table lists the operating wavelength $\lambda$, or wavelength range, in micrometers ($\mu$m). The large range of operating wavelengths, six orders of magnitude, indicates the flexible design characteristics of the FEL mechanism. The second column describes the electron pulse length divided by the speed of light $c$, and ranges from CW to short picosecond pulse time scales. The expected optical pulse length can be 5 to 10 times shorter or longer than the electron pulse depending the optical cavity $Q$, the FEL desynchronism, and the FEL gain. Most FEL oscillators produce an optical spectrum that is Fourier transform limited by the optical pulse length.

The electron beam energy $E$ and peak current $I$ provided by the accelerator are listed in the third and fourth columns in units of MeV and Amperes. The accelerator type is listed as the first entry in the last column with a code such as RF for the radio-frequency linac. While there are a variety of accelerators used, about 75% are RF and about 15% are electron storage rings. Storage rings tend to be used for the short wavelength applications, while the electrostatic accelerators provide longer wavelengths.

The next three columns list the number of undulator periods $N$, the undulator wavelength $\lambda_0$ in centimeters, and the undulator parameter $K = e\bar{B}\lambda_0/2\pi mc^2$ where $e$ is the electron charge magnitude, $\bar{B}$ is the rms undulator field strength, and $m$ is the electron mass. For an FEL klystron undulator, there are multiple undulator sections as listed in the $N$-column. Note that the range of values for $N$, $\lambda_0$, and $K$ are much smaller than for the other parameters indicating that most undulators are similar. Only about 15% of the FELs use the klystron undulator, none use the tapered undulator at present, and the rest use the conventional periodic undulator. The FEL resonance condition,

$$\lambda = \frac{\lambda_0(1+K^2)}{2\gamma^2},$$

where $\gamma$ is the relativistic Lorentz factor $\gamma = E/mc^2$, provides a relationship that can used to derive $K$ from $\lambda$, $E$, and $\lambda_0$. The middle entry of the last column lists the FEL type: "O" for oscillator, "A" for amplifier, etc. Less than 10% of the FELs are amplifiers, while the rest are FEL oscillators. A reference describing the FEL is provided at the end of each line entry.

For the conventional undulator, the peak optical power can be estimated by the fraction of the electron beam peak power that spans the undulator spectral bandwidth, $1/4N$, or $P \approx EI/4eN$. For the FEL using a storage ring, the optical power causing saturation is substantially less than this estimate and depends on ring properties. For the high-gain FEL amplifier, the optical power at saturation can be substantially more. The average FEL power is determined by the duty cycle, or spacing between electron pulses, and is generally many orders of magnitude lower than the peak power.

In the FEL oscillator, the optical mode that best couples to the electron beam in an undulator of length $L = N\lambda_0$ has Rayleigh length $z_0 \approx L/\sqrt{12}$ and has a mode waist radius of $w_0 \approx \sqrt{N}\,\gamma\lambda/\pi$. The FEL optical mode typically has more than 90% of the power in the fundamental mode described by these parameters.

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Relativistic short wavelength free electron lasers (1994)

| FEL | $\lambda$ ($\mu$m) | $\sigma_z$ | $E$ (MeV) | $I$ (A) | $N$ | $\lambda_0$ (cm) | $K$ | Accelerator, type [a] [Ref.] |
|---|---|---|---|---|---|---|---|---|
| Existing FELs | | | | | | | | |
| UCSB (mm FEL) | 340 | 25 $\mu$s | 6 | 2 | 42 | 7.1 | 0.7 | EA, O [1] |
| Stanford (FIRFEL) | 80–200 | 15 ps | 4 | 8 | 50 | 1 | 0.7 | RF, O [39] |
| UCSB (FIR FEL) | 60 | 25 $\mu$s | 6 | 2 | 150 | 2 | 0.1 | EA, O [1] |
| Tokyo (UT-FEL) | 43 | 10 ps | 13 | 20 | 40 | 4 | 0.7 | RF, O [2] |
| Netherlands (FELIX) | 40 | 5 ps | 25 | 50 | 38 | 6.5 | 1.5 | RF, O [3] |
| Osaka (ISIR) | 40 | 30 ps | 17 | 50 | 32 | 6 | 1 | RF, O [24] |
| Bruyeres (ELSA) | 20 | 30 ps | 18 | 100 | 30 | 3 | 0.8 | RF, O [4] |
| Stanford (FIREFLY) | 20–100 | 2 ps | 20 | 6 | 25 | 6 | 1 | RF, O [29] |
| Frascati (LISA) | 15 | 7 ps | 25 | 5 | 50 | 4.4 | 1 | RF, O [5] |
| Grumman (CIRFEL) | 14 | 5 ps | 14 | 150 | 73 | 1.4 | 0.2 | RF, O [23] |
| Beijing (IHEP) | 10 | 4 ps | 30 | 14 | 50 | 3 | 1 | RF, O [6] |
| Orsay (CLIO) | 8 | 0.3 ps | 50 | 80 | 48 | 4 | 1 | RF, O [7] |
| LANL (AFEL) | 4–6 | 10 ps | 15 | 200 | 24 | 1 | 0.3 | RF, O [8] |
| Darmstadt (IR-FEL) | 5 | 2 ps | 40 | 2.7 | 80 | 3.2 | 1 | RF, O [9] |
| Stanford (SCAFEL) | 3–10 | 0.7 ps | 37 | 10 | 72 | 3.1 | 0.8 | RF, O [10] |
| Vanderbilt (FELI) | 3 | 1 ps | 43 | 50 | 47 | 2.3 | 1 | RF, O [11] |
| Duke (Mark III) | 3 | 3 ps | 44 | 20 | 47 | 2.3 | 1 | RF, O [12] |
| BNL (ATF) | 0.5 | 6 ps | 50 | 100 | 70 | 0.88 | 0.4 | RF, O [36] |
| LANL (APEX) | 0.37 | 10 ps | 46 | 140 | 73 | 1.4 | 0.6 | RF, O [13] |
| Tsukuba (NIJI-IV) | 0.35 | 160 ps | 300 | 5 | $2\times42$ | 7.2 | 2 | SR, O [14] |
| Orsay (Super-ACO) | 0.35 | 250 ps | 800 | 0.1 | $2\times10$ | 13 | 4 | SR, O [15] |
| Okazaki (UVSOR) | 0.3 | 6 ps | 500 | 5 | $2\times8$ | 11 | 2 | SR, O [16] |
| BNL (ATF-UV) | 0.25 | 6 ps | 70 | 100 | 70 | 0.88 | 0.4 | RF, O [36] |
| Novosibirsk (VEPP) | 0.24 | 35 ps | 350 | 6 | $2\times33$ | 10 | 1.6 | SR, O [17] |
| Proposed FELs | | | | | | | | |
| Florida (CREOL) | 200–600 | CW | 1.7 | 0.2 | 185 | 0.8 | 0.15 | EA, O [18] |
| Netherlands (TEUFEL) | 180 | 20 ps | 6 | 350 | 50 | 2.5 | 1 | RF, O [38] |
| Rutgers (IRFEL) | 140 | 25 ps | 38 | 1.4 | 50 | 20 | 1 | MA, O [19] |
| Moscow (Lebedev) | 100 | 20 ps | 30 | 0.25 | 35 | 3.2 | 0.8 | MA, O [21] |
| Tokai (SCARLET) | 40 | 40 ps | 15 | 10 | 62 | 3.3 | 1 | RF, O [20] |
| LBL (IRFEL) | 3–50 | 30 ps | 55 | 60 | 40 | 5 | 1 | RF, O [22] |
| CEBAF (IRFEL) | 2–24 | 2 ps | 50 | 100 | 25 | 6 | 2 | RF, O [25] |
| Boeing (APLE) | 10 | 60 ps | 17 | 140 | 100 | 2.4 | 0.2 | RF, O [27] |
| Boeing (APLE) | 10 | 20 ps | 34 | 450 | 257 | 3.9 | 1.2 | RF, A [27] |
| Stanford (FEL) | 10 | 4 ps | 24 | 25 | 52 | 2.6 | 0.9 | RF, O [28] |
| Osaka (ILT) | 10 | 2 ps | 9 | 100 | 30 | 0.66 | 0.3 | RF, O [20] |
| UCLA (IRFEL) | 10 | 2 ps | 20 | 200 | 40 | 1.5 | 1 | RF, A [35] |
| Novosibirsk (RTM) | 7 | 50 ps | 51 | 100 | $4\times40$ | 9 | 1 | RF, O [26] |
| BNL (HGHG) | 3.4 | 10 ps | 30 | 110 | 83 | 1.8 | 1.4 | RF, A [37] |
| CEBAF (UVFEL) | 0.15–2 | 0.4 ps | 200 | 200 | 48 | 3 | 1.5 | RF, O [31] |
| Osaka (FELI) | 1 | 2 ps | 170 | 100 | 50 | 6 | 1.3 | RF, O [20] |
| Rocketdyne (FEL) | 0.84 | 3 ps | 90 | 500 | 160 | 2.4 | 1.4 | RF, MOPA [40] |
| Dortmund (DELTA) | 0.4 | 50 ps | 500 | 90 | 17 | 25 | 2 | SR, O [30] |
| Harima (HIT) | 0.28 | 100 ps | 500 | 3 | 170 | 1.8 | 4.2 | SR, O [20] |
| BNL (DUVFEL) | 0.075 | 6 ps | 310 | 300 | 682 | 2.2 | 1.5 | RF, A [32] |
| Duke (Ring) | 0.05 | 10 ps | 1000 | 350 | $2\times33$ | 10 | 1.7 | SR, O [33] |
| SLAC (LCLS) | 0.0004 | 0.1 ps | 7000 | 2500 | 723 | 8.3 | 4.4 | RF, A [34] |

[a] RF: RF linac accelerator; MA: microtron accelerator; SR: electron storage ring; EA: electrostatic accelerator; A: FEL amplifier; O: FEL oscillator; MOPA: master-oscillator power-amplifier.

## References


[1] G. Ramian, Nucl. Instr. and Meth. A 318 (1992) 225.
[2] E. Nishimura et al., Nucl. Instr. and Meth. A 341 (1994) 39.
[3] D.A. Jaroszynski et al., Nucl. Instr. and Meth. A 331 (1993) 52.
[4] P. Guimbal et al., Nucl. Instr. and Meth. A 341 (1994) 43.
[5] M. Castellano et al., Nucl. Instr. and Meth. A 304 (1991) 204.
[6] J. Xie et al., Nucl. Instr. and Meth. A 331 (1993) 204; Nucl. Instr. and Meth. A 341 (1994) 34.
[7] J.M. Ortega et al., Nucl. Instr. and Meth. A 341 (1994) 138; R. Prazeres et al., Nucl. Instr. and Meth. A 341 (1994) 54.
[8] D.C. Nguyen et al., Nucl. Instr. and Meth. A 341 (1994) 29.
[9] J. Auerhammer et al., Nucl. Instr. and Meth. A 341 (1994) 63.
[10] T. Smith and A. Marziali, Nucl. Instr. and Meth. A 331 (1993) 59; T.I. Smith et al., Proc. SPIE 1854 (1993) 23.
[11] C. Brau, Nucl. Instr. and Meth. A 318 (1992) 38.
[12] S.V. Benson et al., Nucl. Instr. and Meth. A 250 (1986) 39.
[13] P.G. O'Shea et al., Nucl. Instr. and Meth. A 341 (1994) 7.
[14] T. Yamazaki et al., Nucl. Instr. and Meth. A 331 (1993) 27; T. Yamazaki et al., Nucl. Instr. and Meth. A 341 (1994) ABS 3.
[15] T. Hara et al., Nucl. Instr. and Meth. A 341 (1994) 21.
[16] S. Takano et al., Nucl. Instr. and Meth. A 331 (1993) 20; H. Hama et al., Nucl. Instr. and Meth. A 341 (1994) 12.
[17] I.B. Drobyasko et al., Nucl. Instr. and Meth. A 282 (1989) 424.
[18] L.R. Elias et al., Nucl. Instr. and Meth. A 304 (1991) 2919; M. Tecimen, Nucl. Instr. and Meth. A 341 (1994) 219.
[19] E.D. Shaw et al., Nucl. Instr. and Meth. A 318 (1992) 47.
[20] N. Ohigashi et al., presented at this Conference (16th Int. Free Electron Laser Conf. Standford, CA, USA, 1994).
[21] K.A. Belovintsey et al., Nucl. Instr. and Meth. A 341 (1994) ABS 45; A. Agafonov et al., Nucl. Instr. and Meth. A 331 (1993) 186.
[22] K.J. Kim et al., Nucl. Instr. and Meth. A 341 (1994) 280.
[23] I.S. Lehrman et al., Nucl. Instr. and Meth. A 341 (1994) ABS 31.
[24] S. Okuda et al., Nucl. Instr. and Meth. A 341 (1994) 59.
[25] G. Neil, Nucl. Instr. and Meth. A 318 (1992) 212; G. Neil et al., Nucl. Instr. and Meth. A 341 (1994) ABS 39.
[26] N.A. Vinokurov et al., Nucl. Instr. and Meth. A 331 (1993) 3.
[27] D. Quimby et al., Nucl. Instr. and Meth. A 318 (1992) 696.
[28] J.F. Schmerge and R. Pantell, Nucl. Instr. and Meth. A 341 (1994) 335.
[29] T.I. Smith et al., Proc. SPIE 1854 (1993) 23; A. Schwettman et al., Nucl. Instr. and Meth. A 341 (1994) ABS 19.
[30] D. Nolle et al., Nucl. Instr. and Meth. A 341 (1994) ABS 7; Schmidt et al., Nucl. Instr. and Meth. A 341 (1994) ABS 9.
[31] G. Neil, High-Power UV FEL For Industrial Processing, The Laser Processing Consortium Proposal (1994).
[32] S. Krinsky (Ed.), The BNL DUV FEL Report (1994).
[33] J.M.J. Madey et al., Nucl. Instr. and Meth. A 341 (1994) 363.
[34] C. Pellegrini et al., Nucl. Instr. and Meth. A 341 (1994) 326.
[35] G. Baranov et al., Nucl. Instr. and Meth. A 331 (1993) 228.
[36] K. Batchelor et al., Nucl. Instr. and Meth. A 318 (1992) 159.
[37] I. Ben-Zvi et al., Nucl. Instr. and Meth. A 318 (1992) 208.
[38] J.I.M. Botman et al., Nucl. Instr. and Meth. A 341 (1994) 402.
[39] R.H. Pantell et al., presented at this Conference (16th Int. Free Electron Laser Conf. Stanford, CA, USA, 1994).
[40] R.J. Burke et al., Proc. SPIE: Laser Power Beaming, Los Angeles, Jan. 27–28, 1994, Vol. 2121.